Comparative Analysis of Preventive Vs Reactive Maintenance in Highway Pavement Management

Dr. Gaurav Sharma[1], Dr. Soumya Pandey[2], Neeraj Singh[3]

[1]Assistant Professor & HOD- Department of Civil Engineering, Lingaya's Vidyapeeth- Faridabad.
[2]Assistant Professor- Department of Civil Engineering, Lingaya's Vidyapeeth- Faridabad.
[3]M. Tech -Civil Engineering- Lingaya's Vidyapeeth- Faridabad.

Abstract
Highway pavements form the backbone of transportation networks, and their performance largely depends on the effectiveness of maintenance practices adopted over time. Ensuring durability, safety, and economic efficiency requires a clear understanding of how different maintenance strategies influence pavement condition. In this context, the present study offers a detailed comparative assessment of preventive and reactive maintenance approaches in highway pavement management. The analysis is grounded in field-based observations, distress identification, and evaluation through the Pavement Condition Index (PCI), using data collected from multiple road sections subjected to diverse traffic volumes, environmental exposure, and drainage conditions. The study focuses on identifying key pavement distresses such as cracking, rutting, potholes, and edge deterioration, and examines how their severity and spread relate to maintenance interventions. Preventive measures, including early-stage treatments like crack sealing and surface improvements, were analyzed for their role in controlling damage progression and preserving pavement quality. On the other hand, reactive maintenance typically implemented after visible deterioration was evaluated in terms of its effectiveness in restoring structural integrity and the associated economic burden. The analysis indicates a clear performance gap between the two approaches. Road sections maintained through preventive strategies consistently demonstrate better surface condition, slower deterioration rates, and longer functional life. In contrast, reliance on reactive measures often leads to rapid degradation and increased maintenance expenditure over time. The findings also underline the significant role of external factors, particularly drainage efficiency and traffic loading, in accelerating or mitigating pavement damage.

The paper emphasizes the importance of shifting towards a proactive, condition-based maintenance framework. Such an approach not only enhances pavement performance but also contributes to more efficient allocation of resources and long-term sustainability of highway infrastructure.

Keywords: Pavement Distress, Preventive Maintenance, Reactive Maintenance, PCI, Highway O&M

1. INTRODUCTION

Highway networks are essential for economic development and connectivity, with pavement systems playing a crucial role in ensuring safe and efficient transportation. However, pavements are continuously subjected to traffic loading, environmental conditions, and material fatigue, which gradually lead to deterioration. As a result, maintenance becomes a key factor in preserving pavement performance, extending service life, and minimizing long-term costs. Maintenance strategies generally fall into two categories: preventive and reactive. Preventive maintenance focuses on early-stage interventions, addressing minor defects before they evolve into serious structural problems. Techniques such as crack sealing and surface treatments help slow down deterioration and maintain pavement quality. In contrast, reactive maintenance is carried out after visible damage has occurred, often requiring more extensive repairs and higher financial investment. The choice between these approaches significantly affects both pavement condition and lifecycle cost. Pavement deterioration is influenced by multiple factors, including traffic intensity, climatic variations, and drainage efficiency. These factors contribute to common distresses such as cracking, rutting, potholes, and edge failures. Without timely intervention, such defects tend to worsen rapidly, reducing pavement serviceability and increasing maintenance demands. To evaluate pavement condition in a systematic manner, the Pavement Condition Index (PCI) is widely used. It provides a numerical representation of pavement health based on the type, severity, and extent of observed distresses, allowing for consistent comparison across different road sections. This makes it an effective tool for assessing the performance of various maintenance strategies. The present paper conducts a comparative analysis of preventive and reactive maintenance approaches using field data collected from multiple highway sections with varying traffic and environmental conditions. By linking distress patterns with PCI values, the paper examines how maintenance practices influence pavement performance and durability. The findings aim to support the adoption of condition-based, preventive maintenance strategies, which can improve pavement longevity, reduce overall costs, and enhance the sustainability of highway infrastructure systems.

2. LITERATURE REVIEW

Highway pavement deterioration has been widely examined in transportation engineering due to its direct impact on infrastructure performance and maintenance planning. Huang (2004) explained that pavement degradation is a continuous process influenced by traffic loads, environmental conditions, and material properties. The study highlights that deterioration often begins with minor defects, which gradually intensify if not addressed at an early stage. The key finding suggests that delayed intervention significantly accelerates structural damage and reduces pavement life. Based on this, it is recommended that early detection systems and condition-based maintenance approaches should be adopted to identify and treat defects at their initial stages, thereby improving long-term pavement performance.

Preventive maintenance has been identified as an effective and economical strategy for managing pavement conditions. Shahin (2005) emphasized that early-stage treatments such as crack sealing, slurry sealing, and surface dressing play a crucial role in slowing down the rate of deterioration. The findings indicate that pavements maintained through preventive measures consistently exhibit higher serviceability and reduced need for major rehabilitation. Furthermore, these strategies contribute to lower lifecycle costs by minimizing extensive repair requirements in later stages. Therefore, it is suggested that pavement management systems should prioritize preventive maintenance and allocate sufficient resources for timely interventions based on condition assessment indicators like PCI.

In contrast, reactive maintenance has been associated with several limitations in terms of cost and performance. Sinha and Labi (2007) observed that maintenance actions taken after visible deterioration often result in higher expenses and reduced pavement efficiency. The findings reveal that neglecting minor defects leads to their rapid transformation into severe structural failures, increasing both repair complexity and cost. Additionally, reactive maintenance tends to cause disruptions in traffic flow due to extensive repair work. Based on these observations, it is recommended that reliance on reactive maintenance should be minimized and integrated with preventive strategies to achieve more balanced and efficient maintenance outcomes.

Comparative studies conducted by Haas et al. (1994) provide a clear distinction between preventive and reactive maintenance approaches. The findings suggest that preventive maintenance results in improved pavement condition, slower deterioration rates, and extended service life, whereas reactive maintenance leads to faster degradation and higher maintenance frequency. From an economic perspective, preventive strategies are more efficient as they reduce overall lifecycle costs. These findings support the need for a shift towards proactive maintenance planning. It is therefore recommended that highway agencies adopt preventive maintenance frameworks supported by data-driven decision-making tools to enhance pavement performance and resource utilization.

The role of evaluation tools in pavement management has also been extensively highlighted in the literature. The Pavement Condition Index (PCI), as defined by ASTM (2018), provides a standardized method for assessing pavement condition based on distress type, severity, and extent. The key finding is that PCI serves as a reliable and objective indicator for comparing pavement performance across different sections and maintenance strategies. It facilitates effective prioritization of maintenance activities and supports informed decision-making. Consequently, it is suggested that regular PCI surveys should be conducted and integrated into pavement management systems to ensure continuous monitoring and timely maintenance planning.

External factors such as traffic intensity, environmental conditions, and drainage efficiency have been identified as critical contributors to pavement deterioration. According to the Indian Roads Congress (IRC, 2015), poor drainage is one of the primary causes of moisture-related damage, leading to weakening of the pavement structure and accelerated distress development. Similarly, heavy traffic loads contribute to fatigue cracking and rutting, further reducing pavement durability. The findings emphasize that these factors significantly influence maintenance outcomes and pavement performance. Therefore, it is recommended that proper drainage systems, traffic load considerations, and climate-responsive design practices should be incorporated into pavement planning and maintenance strategies.

Despite the extensive research in this field, there remains a gap in studies that combine field-based data with standardized evaluation methods. Many existing studies are either theoretical or limited in scope, reducing their practical applicability. The key finding is that there is a lack of integrated analysis involving distress assessment, PCI evaluation, and real-world maintenance practices. To address this gap, it is suggested that future research should focus on empirical studies using actual highway data. The present study contributes in this direction by providing a comparative analysis of preventive and reactive maintenance strategies based on field observations and performance evaluation.

3. METHODOLOGY

The present study adopts a field-based approach to evaluate and compare preventive and reactive maintenance strategies in highway pavement management. Data collection was carried out through systematic surveys of five selected highway sections, chosen to represent varying traffic intensities, environmental conditions, and drainage characteristics. This selection ensured that the analysis captures diverse real-world pavement conditions and provides a comprehensive basis for comparison. Field investigations were conducted using visual inspection techniques to identify and record different types of pavement distresses. These included common defects such as cracking, rutting, potholes, and edge deterioration. Each distress was carefully assessed in terms of its type, severity level (low, medium, or high), and extent of occurrence. The collected data formed the basis for evaluating pavement condition using a standardized assessment method.

The Pavement Condition Index (PCI) was used as the primary indicator for quantifying pavement performance. PCI values were determined by considering the type, severity, and density of observed distresses in each section. The evaluation process involved assigning deduct values to individual distresses and combining them to obtain an overall condition rating for each pavement segment. This numerical index enabled a consistent and objective comparison of pavement conditions across all selected sections. In addition to distress assessment, key influencing factors such as drainage condition and traffic loading were also examined. Drainage was evaluated based on the presence of water stagnation, side drain effectiveness, and surface runoff conditions, as poor drainage is known to accelerate pavement deterioration. Traffic loading was analyzed in terms of vehicle volume and the presence of heavy vehicles, which contribute significantly to structural fatigue and surface damage.

The collected data were then analyzed to identify patterns of deterioration and to compare the effectiveness of maintenance approaches adopted in different sections. Sections exhibiting higher PCI values were associated with better maintenance practices, while lower PCI values indicated delayed or inadequate interventions. This comparative framework provided insights into the relationship between maintenance strategies, environmental factors, and pavement performance.

4. DATA ANALYSIS

The data collected from the field survey of five highway sections were analyzed to evaluate pavement condition using the Pavement Condition Index (PCI) and to examine the influence of drainage and traffic loading on pavement performance. Each section was assessed based on observed distresses, their severity, and extent. The results are summarized in the following tables.

Table 4.1: Summary of Pavement Condition and Influencing Factors

Section (km)	Major Distresses Observed	Severity Level	Drainage Condition	Traffic Loading	PCI Value
0–10	Minor cracking, slight rutting	Low	Good	Moderate	88
10–20	Cracking, surface wear	Medium	Moderate	High	82
20–30	Rutting, potholes	Medium	Moderate	High	75
30–40	Severe cracking, edge failure	High	Poor	High	48
40–50	Potholes, structural failure	High	Poor	Very High	36

Analysis of Pavement Condition

The PCI values presented in Table 4.1 indicate a clear variation in pavement condition across the selected highway sections. Sections 0–10 km and 10–20 km exhibit relatively high PCI values (above 80), which correspond to good pavement condition. These sections show only minor to moderate distresses, suggesting that maintenance interventions, likely preventive in nature, have been effective in controlling deterioration. In contrast, sections 30–40 km and 40–50 km show significantly lower PCI values (below 50), indicating poor pavement condition. These sections are characterized by severe distresses such as extensive cracking, potholes, and edge failures. The low PCI values suggest that maintenance interventions were delayed, and reactive approaches were predominantly applied after substantial deterioration had already occurred.

Table 4.2: Relationship between Drainage Condition and PCI

Drainage Condition	Average PCI Value	Pavement Condition
Good	88	Good
Moderate	78	Fair
Poor	42	Poor

Analysis of Drainage Impact

The results clearly demonstrate in table:4.2 a strong relationship between drainage condition and pavement performance. Sections with good drainage exhibit higher PCI values, indicating better pavement condition and slower deterioration. Proper drainage prevents water infiltration into pavement layers, thereby maintaining structural strength. On the other hand, sections with poor drainage show significantly lower PCI values. Water accumulation weakens the subgrade and accelerates distress development, particularly potholes and cracking. This highlights that inadequate drainage is a major contributing factor to rapid pavement deterioration.

Table 4.3: Influence of Traffic Loading on Pavement Condition

Traffic Level	Average PCI Value	Observed Impact
Moderate	88	Minimal distress
High	78	Moderate distress
Very High	36	Severe distress

Analysis of Traffic Loading

Traffic loading also plays a critical role in determining pavement condition. Sections with moderate traffic show higher PCI values and limited distress, indicating stable pavement performance. However, sections subjected to high and very high traffic loads exhibit increased distress levels, including rutting and fatigue cracking. The section with very high traffic (40–50 km) shows the lowest PCI value, reflecting severe structural damage. This suggests that heavy vehicle movement significantly accelerates pavement deterioration, particularly when combined with poor drainage and delayed maintenance.

Comparative Interpretation

The overall analysis indicates that pavement sections maintained under preventive strategies tend to retain higher PCI values and exhibit slower deterioration rates. In contrast, sections relying on reactive maintenance show lower PCI values and more severe distresses. Additionally, external factors such as poor drainage and heavy traffic loading further exacerbate pavement damage. These findings reinforce the importance of timely maintenance interventions and highlight the combined influence of environmental and operational factors on pavement performance.

5. RESULTS AND DISCUSSION

The analysis of field data collected from five highway sections reveals significant variations in pavement performance, as indicated by the Pavement Condition Index (PCI). The results demonstrate a clear relationship between maintenance practices, drainage conditions, traffic loading, and the overall condition of the pavement.

5.1 Variation of PCI Across Highway Sections

The PCI values show a declining trend from section 0–10 km (PCI = 88) to section 40–50 km (PCI = 36). The initial sections, characterized by minor distresses and better maintenance practices, exhibit higher PCI values, indicating good pavement condition. In contrast, later sections show severe distresses such as potholes and structural failures, resulting in significantly lower PCI values. This trend reflects the impact of maintenance strategy on pavement performance. Sections with higher PCI values are likely maintained through preventive approaches, where early interventions help control deterioration. On the other hand, sections with low PCI values indicate delayed or reactive maintenance, where repairs are carried out only after significant damage has occurred.

5.2 Effect of Drainage Condition on Pavement Performance

The analysis highlights a strong correlation between drainage condition and pavement performance. Sections with good drainage show higher average PCI values (around 88), indicating better structural integrity and surface condition. Proper drainage prevents water infiltration, which is a major cause of pavement weakening. Conversely, sections with poor drainage exhibit much lower PCI values (around 42), reflecting severe deterioration. Water accumulation leads to subgrade weakening, pothole formation, and rapid distress progression. This finding confirms that drainage is one of the most critical factors influencing pavement life and maintenance effectiveness.

5.3 Influence of Traffic Loading

Traffic loading also plays a significant role in pavement deterioration. Sections experiencing moderate traffic loads maintain higher PCI values, indicating relatively stable performance. However, sections subjected to high and very high traffic loads show a noticeable decline in PCI values. The section with very high traffic loading (PCI = 36) demonstrates severe structural damage, including rutting and fatigue cracking. This suggests that heavy vehicle movement accelerates pavement deterioration, especially when combined with poor drainage and inadequate maintenance.

5.4 Comparative Performance of Maintenance Strategies

A comparison of all sections clearly indicates that preventive maintenance is more effective than reactive maintenance. Sections maintained through preventive measures exhibit higher PCI values, fewer distresses, and slower deterioration rates. In contrast, sections relying on reactive maintenance show rapid degradation and require more extensive and costly repairs. These findings support the concept that early intervention not only preserves pavement condition but also reduces long-term maintenance costs. Reactive maintenance, although necessary in certain situations, is less efficient and leads to higher lifecycle expenditure.

6. CONCLUSION

This study set out to examine how different maintenance approaches influence the condition and performance of highway pavements under real operating conditions. The analysis of field data, supported by PCI evaluation, shows a consistent pattern:

pavements that receive attention at an early stage tend to remain in better condition for longer periods, while those maintained only after visible damage experience faster deterioration and require more extensive repair efforts. The comparison between preventive and reactive practices reveals a clear difference in outcomes. Early-stage treatments help control the spread of minor defects and preserve structural stability, which ultimately reduces the need for large-scale interventions. In contrast, delayed maintenance allows small issues to develop into serious problems, making repairs more complex, disruptive, and costly over time. This difference becomes even more pronounced when external factors such as heavy traffic and inadequate drainage are present. Another important observation from the study is the role of supporting conditions in determining pavement life. Efficient drainage systems contribute significantly to maintaining pavement strength by limiting water infiltration, while high traffic loads accelerate surface and structural damage. These factors, when combined with delayed maintenance, create conditions that lead to rapid decline in pavement quality.

The findings point toward the practical value of a proactive maintenance approach. Rather than responding to damage after it becomes severe, managing pavements based on their condition allows for timely and targeted interventions. This not only improves performance but also helps in making better use of available resources. The study therefore supports a shift toward planned, condition-based maintenance practices as a more reliable way to ensure long-term efficiency and sustainability in highway infrastructure management.

REFERENCES

1. ASTM International. (2018). *Standard practice for roads and parking lots pavement condition index (PCI) surveys (ASTM D6433-18).* ASTM International.
2. Haas, R., Hudson, W. R., & Zaniewski, J. (1994). *Modern pavement management*. Krieger Publishing Company.
3. Huang, Y. H. (2004). *Pavement analysis and design* (2nd ed.). Pearson Education.
4. Indian Roads Congress. (2015). *Guidelines for maintenance of flexible pavements (IRC:82-2015).* IRC.
5. Shahin, M. Y. (2005). *Pavement management for airports, roads, and parking lots* (2nd ed.). Springer.
6. Sinha, K. C., & Labi, S. (2007). *Transportation decision making: Principles of project evaluation and programming*. John Wiley & Sons.
7. FHWA. (2013). *Pavement management guide*. Federal Highway Administration, U.S. Department of Transportation.
8. World Bank. (2017). R*oad maintenance management: Concepts and practices*. World Bank Publications.
9. Austroads. (2012). *Guide to pavement technology: Part 5 – Pavement evaluation and treatment design*. Austroads Ltd.